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CDF B Spectroscopy Results: B** and B$_c^+$

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Abstract

We report on two spectroscopy results from CDF. First, we observe the orbitally excited B^{**} mesons in $B \to \ell D^{(*)} X$ events. We find $28 \pm 6 \pm 3\%$ of light B mesons produced are B^{**} states. A collective mass fit results in a B_1 mass of 5.71 ± 0.02 GeV$/c^2$. Secondly, we observe $20.4^{+6.2}_{-5.5}$ decays of $B_c^+ \to J/\psi \ell^+ X$, with a $6.40 \pm 0.39 \pm 0.13\,\mathrm{GeV}/c^2$ mass and $0.46^{+0.18}_{-0.16} \pm 0.03\,$ps lifetime. The production rate is in reasonable accordance with expectations.

1. Introduction

The large b cross section at the Tevatron make it an attractive arena for studying b-hadrons. CDF has reported a variety of spectroscopy results, including the most precise mass determinations of the B_s^0 [1] and Λ_b^0 [2]. Here we report results on the rare B_c^+, and the not rare, but hard to observe, B^{**} states.

2. B^{**} production

The B^{**} states are the 4 orbitally ($L = 1$) excited states of the B meson. In a relativistic light-quark model the states B_1, B_2^*, B_0^*, and B_1^* have masses 5.719, 5.733, 5.738, and 5.757 GeV$/c^2$ [3]. Being above the π-threshold, they decay via $B^{**} \to B^{(*)}\pi$. The normally broad ($\sim$100 MeV) hadronic decay width is expected to be suppressed ($\sim$20 MeV) for B_1 and B_2^* because only $L = 2$ decays are allowed.

Study of B^{**}'s is of interest for non-perturbative QCD models, and for "engineering" b-flavor tagging methods [4,5]. B^{**}'s have been observed in e^+e^- collisions [6]. Here we report the first observation of B^{**}'s in a hadron collider.

We use $110\,\mathrm{pb}^{-1}$ of data collected in Run I. We reconstruct 6 modes of the type $B \to D^{(*)}\ell X$ [7], all of which have been previously documented [5] except for the addition of $\ell^+\overline{D}^0$, $\overline{D}^0 \to K^+\pi^-\pi^+\pi^-$. Side-band subtractions are performed, and we effectively obtain a pure sample of almost 10^4 B's.

B^{**}'s should be narrow peaks on a broad structure in the $B\pi$ mass. Even after kinematic corrections ($\sim$15%) the lost ν, as well as the unidentified γ from B^* decay, smears these peaks. With background, it is then extremely difficult to identify B^{**}'s. These problems are ameliorated by using the quantity $Q \equiv m[\ell D^{(*)}\pi] - m[\ell D^{(*)}] - m[\pi]$ which compresses the broad $m[\ell D^{(*)}\pi]$ distribution (with $\ell D^{(*)} \approx B$) into a relatively narrow range at low Q.

We combine B's with tracks ($p_T > 0.9\,\mathrm{GeV}/c$), assumed to be π's, from the primary vertex (impact parameter $< 3\sigma$) to form B^{**} candidates. These B-π combinations contain a variety of backgrounds uncorrelated to the B: random π's from the underlying event and from multiple $\bar{p}p$ collisions. These backgrounds may be removed by "sideband subtraction" methods. The major remaining background is from pions from the hadronization of the B, which, unfortunately, *is* correlated with the B, and thus demands careful treatment.

B^{**} decays give $B^+\pi^-$ or $B^0\pi^+$ ("right-sign") combinations at low-Q, and not $B^+\pi^+$ or $B^0\pi^-$ ("wrong-sign"). The B-π Q-distributions, divided into B^+ and B^0 mesons and into right/wrong-sign categories, are shown in Fig. 1. The data (points) show a clear right-sign excess, but B^+ and B^0 behave differently and the wrong-sign background peaks in the same Q-region. The B^{**} signal is entangled with the hadronization background which also favors the right-sign at low Q-values (the basis for our "same side tagging" [4,5]). Thus, one can not expose a B^{**} signal by subtracting the "wrong-sign" Q-distributions from the "right-sign" ones.

We model the hadronization Q-distributions by 2-parameter functions inspired by PYTHIA [8], and impose the *relative* right/wrong-sign hadronization asymmetry from the simulation. We fit the data for B^{**} signal plus this hadronization model.‡

‡ Other small backgrounds, such as B_s^{**}, are included. The

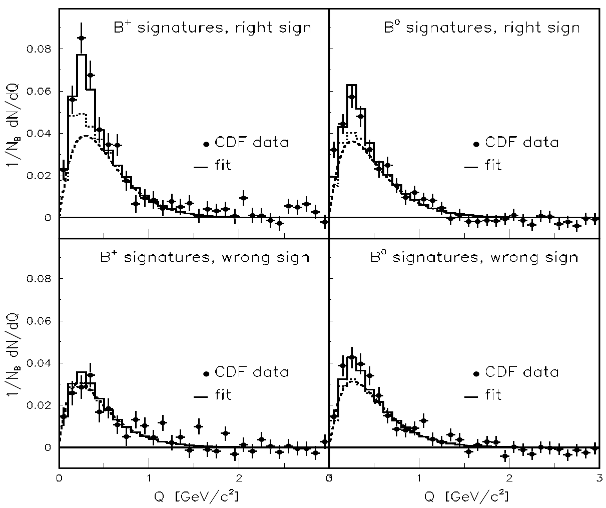

Figure 1. The sideband-subtracted Q-distributions divided into B^+/B^0 modes and right/wrong-sign $B\pi^\pm$ combinations: data (points), fit (solid histogram), total background (dotted histogram), and hadronization background (dashed curve).

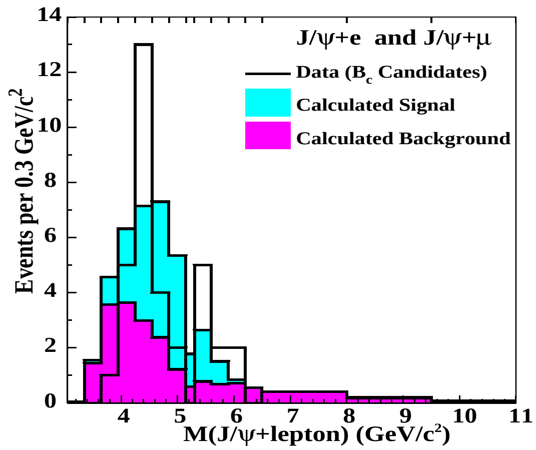

Figure 2. The $J/\psi + \ell^+$ mass distributions of data, and the calculated background and signal.

The specific *shape* of the hadronization background, as well as its overall normalization, and the amount of any B^{**} signal are free to float in the fit.

The solid histogram in Fig. 1 shows the fit, with the dotted histogram showing the total background and the dashed curve is the hadronization component. The excess above the total background (dotted) is the B^{**} signal, which is even in the wrong-sign events. B^0-mixing moves events between right-sign B^0's and wrong-sign B^0's, creating an apparent asymmetry between the B^{**} signal in B^+'s and B^0's. There is a small amount of cross-talk between B^+ and B^0 reconstructions (*e.g.* if the π^- is lost from $D^{*-} \to \overline{D}^0\pi^-$), which shifts B^{**}'s diagonally in Fig. 1, *e.g.*, right-sign B^+ to wrong-sign B^0.

The fit results in a $B\pi$ excess from which we find that B^{**} states are 28±6±3% of light B meson production. The distributions of Fig. 1 are clearly inadequate to distinguish the B^{**} states, but we can use the mass splitting of Ref. [3] and fit the Q-distribution for the collective B^{**} mass. We quote the result in terms of the mass of the lowest state, B_1, as $5.71 \pm 0.02\,(stat. + syst.)$ GeV/c^2. [7]

3. B_c^+ production

The B_c^+ is the ground state of $c\bar{b}$ mesons. It is novel as a bound state of two *different* heavy quarks, and is an interesting test for bound-state models. CDF has previously searched for the $J/\psi\pi^+$ decay, and set upper limits [9]. We extend the search to the higher rate semileptonic mode $B_c^+ \to J/\psi\ell^+\nu$ [10].

We use $\sim$200,000 $J/\psi \to \mu^+\mu^-$ events ($p_T(\mu)$ above $\sim$1.5 GeV/c) fully contained in the Si-μvertex detector (for precision vertexing). A 3rd track is added to the J/ψ compatible (Prob(χ^2)$>$ 1%) with its vertex, and within a cone of 90°. The proper time for the J/ψ+track system must be more than 60μm. This yields 6530 (1055) candidates satisfying electron (muon) fiducial cuts. Lepton identification criteria applied to the 3rd track reduced the sample to 23 (14) electron (muon) candidates.

B_c^+ background comes from two general classes: J/ψ+fake lepton, and J/ψ+real, but uncorrelated, lepton. Fake leptons arise from misidentified hadrons (e^--misidentification, decay-in-flight,...), and uncorrelated leptons from γ-conversions or from the semileptonic decay of a second b-hadron. These backgrounds are determined from data measurements extrapolated via Monte Carlo to the $J/\psi\ell^+$ sample. We find 8.6 ± 2.0 (12.8 ± 2.4) background events in the electron (muon) sample [10].

A likelihood fit of the $J/\psi + \ell^+$ mass distributions (e^+ and μ^+ separated but fit simultaneously), with calculated backgrounds and a B_c^+ component, yields a B_c^+ signal of $20.4^{+6.2}_{-5.5}$ mesons (4.8σ significance). The results are shown in Fig.2.

This sample may be used to extract several B_c^+ properties. Although the missing ν greatly reduces sensitivity to the B_c^+ mass, we find from our fits a value of $6.40 \pm 0.39 \pm 0.13\,\mathrm{GeV}/c^2$. We release the 60 μm "lifetime" cut, correct for the missing ν and resolution effects, and fit the lifetime distribution of Fig. 3 to obtain $\tau(B_c^+) = 0.46^{+0.18}_{-0.16} \pm 0.03$ ps.

We can determine the cross-section×branching-fraction, $\sigma_{Bc}\mathcal{B}(B_c^+ \to J/\psi\ell^+\nu)$, from the event

fit accounts for the important sample composition issues of cross-talk between B^+ and B^0 decays and B^0-mixing.

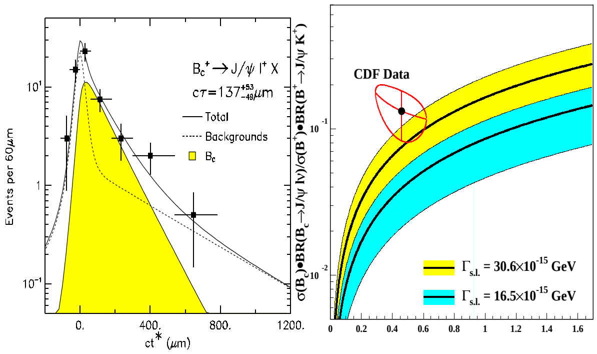

Figure 3. Left: Proper time distribution of the data with lifetime fit. Right: Relative branching ratio $\mathcal{R}(J/\psi\ell^+\nu)$ as a function of B_c^+ lifetime.

yield. We do so, however, relative to the similar $B_u^+ \to J/\psi K^+$ decay since many experimental systematics cancel in the ratio. We find:

$$\mathcal{R}(J/\psi\ell^+\nu) \equiv \frac{\sigma_{Bc} \times \mathcal{B}(B_c^+ \to J/\psi\ell^+\nu)}{\sigma_{Bu} \times \mathcal{B}(B_u^+ \to J/\psi K^+)} = 13.2^{+4.1}_{-3.7}\,(stat) \pm 3.1\,(syst)^{+3.2}_{-2.0}\,(life)\,\%,$$

a rate below LEP sensitivities. This ratio is lifetime dependent, and is shown in Fig. 3 along with theoretical predictions [10]. Two different assumptions for $\Gamma_{s.l.}(B_c^+ \to J/\psi\ell^+\nu)$ are shown.

4. Summary and prospects

We have observed the production of B^{**} states in $\bar{p}p$ collisions, at a relative rate similar to LEP's. Pions from B^{**} decays are likely a significant contribution to "same-side" flavor-tagging methods. Our sample is too limited to unravel the four B^{**} states. Next year, however, Run II of the Fermilab Tevatron [11] will begin where we expect 20× the luminosity ($\sim$2 fb^{-1} in 2 years). Fully exclusive B^{**} reconstructions should be possible with these larger B samples, and the finer mass resolution will aid in the study of these states.

We have also made the first observation of the B_c^+ meson, and performed a initial survey of its properties. The increased data of Run II will enable us to improve all these measurements. This is most notably the case for the B_c^+ mass, as we should be able to fully reconstruct some of its decay modes.

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